Development of a Mathematical Model for Master's Program Curricula Based on Labor Market Needs Analysis

Marine Usepyan
NPUA
Yerevan, Armenia
e-mail: musepyan@polytechnic.am

***Abstract*—Contemporary higher education systems face the imperative of adapting master's programs to the dynamically evolving demands of the labor market. Existing approaches to master's curriculum design often replicate undergraduate-level methodologies, failing to account for the research-oriented nature and specialized focus inherent in master's education. The development of evidence-based methods for integrating employer requirements into educational program structures has become particularly pressing.**

The objective of this study is to develop a mathematical model for the formation of a master's curriculum based on a quantitative analysis of labor market needs and the multi-criteria optimization of educational program structures.

The methodology encompasses stakeholder requirement analysis adapted to master's program specifics, mathematical modeling utilizing objective functions, and iterative optimization algorithms. The study is grounded in survey results from 105 stakeholder representatives.

Experimental validation of the developed mathematical model demonstrated that the proposed framework enables evidence-based design of master's programs aligned with contemporary requirements for training specialists with advanced research competencies. The research findings can be applied to enhance master's degree educational programs.

***Keywords*—master's program curriculum, mathematical modeling, multi-criteria optimization, research-oriented education, competency-based approach.**

I. Introduction

The modern higher education system is undergoing systemic structural transformations driven by technological progress, changing labor market requirements, and the need to train a new type of qualified professionals. This particularly affects master's programs, where both narrow specialization and developed research competencies are required for expert activities.

Master's education fundamentally differs from bachelor's education in its emphasis on the research component, the development of expert competencies, and its orientation toward continuing education in doctoral programs. However, when developing curricula, methodological approaches from the bachelor's level are often applied, which leads to reduced quality of preparation.

Contemporary practice in designing educational programs has critical shortcomings: the absence of mathematically substantiated methods for determining curriculum structure, the prevalence of subjective expert assessments in allocating study time, and the formal consideration of employer requirements without their quantitative integration. These problems are particularly relevant under modern conditions when competency requirements for master's graduates change with high dynamics.

II. Theoretical Foundations of Curriculum Development

The competency-based approach is recognized as the foundation for designing educational programs oriented toward practical learning outcomes [2]. Research on master's education emphasizes the need for balance between fundamental preparation and research skills, with international models including research-based, coursework-based, and mixed approaches [1].

Analysis of IT master's programs shows increased research components to 40-50% of study time [4]. However, a unified methodology for determining optimal component ratios is lacking. While quantitative methods for educational program optimization gain acceptance [5], most mathematical models target bachelor's programs without accounting for master's specifics.

Identified Problems and Contradictions

Three critical issues emerge:

- Absence of specialized methodology - universal methods fail to account for the master's research orientation and expert-level focus;
- Lack of mathematical substantiation - existing approaches rely on subjective assessments rather than objective frameworks;
- Weak labor market integration - formal consideration of employer requirements without quantitative mechanisms [6].

III. Approaches to Solving the Identified Problem

Conceptual Framework of the Study

To address the identified problems, a comprehensive approach is proposed, based on the integration of mathematical methods, the competency-based approach, and stakeholder requirements. The conceptual framework of the study includes four interconnected components: Adapted Requirements Analysis, Mathematical Modeling, Structure Optimization, and Experimental Model Validation.

1. Adapted Requirements Analysis

Master's education differs fundamentally from undergraduate programs in instructional time distribution. While undergraduate programs allocate general education 25-30%, core disciplines 60-65%, and research activities 5-10%, master's programs require 15-20%, 35-40%, and 40-45% respectively. These differences reflect the master's orientation toward preparing researcher-practitioners and expert-level specialists.

Traditional stakeholder surveys require fundamental adaptation for master's programs. Universal questionnaires not accounting for research orientation yield opinions suited for undergraduate preparation, distorting planning results. An adapted questionnaire is proposed that orients stakeholders to evaluate competencies specifically for the master's level with enhanced research components.

Correlation analysis of adapted survey results, detailed in previous studies [7], provides competency weight coefficients corresponding to master's education specificity. Unlike undifferentiated approaches that undervalue research competencies, the adapted methodology ensures correct values for the target 40-45% research allocation in master's programs.

2. Mathematical Modeling of Curricula

A mathematical model for curriculum optimization is proposed, based on quantitative integration of stakeholder requirements and multi-criteria optimization methods. The model comprises three interconnected components: a system of competency weight coefficients, a discipline-competency correspondence matrix, and an algorithm for optimizing curriculum structure.

- Competency Weight Coefficients

Competency weights W_j are determined based on correlation analysis of adapted stakeholder survey results. The procedure includes normalization of competency importance assessments:

$$W_j = \frac{\bar{X}_j}{\sum_{k=1}^{n} \bar{X}_k}, \qquad (1)$$

where $\bar{X}_j$ is the average importance rating of competency j based on stakeholder survey results, and n is the total number of program competencies.

The condition $\sum_{j=1}^{n} W_j = 1$ ensures the correct interpretation of weights as proportions of the total importance of all competencies.

- Discipline-Competency Correspondence Matrix

The level of competency j formation in the curriculum is determined through a correspondence matrix K_{ij}, where each element represents the coefficient of connection between discipline i and competency j ($K_{ij} \in [0,1]$). Coefficients are established through expert assessment based on analysis of course syllabi content and learning outcomes. The competency formation level is calculated as:

$$C_j = \sum_{i=1}^{m} \left(K_{ij} * H_i * T_i\right), \qquad (2)$$

where H_i is the proportion of instructional time allocated to discipline i ($\sum H_i = 1$), T_i is the discipline type coefficient accounting for the specificity of different learning forms (lectures, practicum, research), and m is the total number of disciplines in the curriculum.

- Optimization Objective Function

Curriculum quality in terms of correspondence to labor market requirements is determined by the objective function:

$$F = \sum_{j=1}^{n} \left(W_j * C_j\right) \rightarrow max, \qquad (3)$$

This function maximizes the weighted sum of competency formation levels, where weights reflect their importance for master's professional activity. Physical meaning of the function: the higher the competency importance for the labor market (W_j) and the better it is formed in the curriculum (C_j), the higher the integral assessment of program quality.

3. Curriculum Structure Optimization

Optimization is performed under the following constraints:

a) **Time normalization:** $\sum_{i=1}^{m} H_i = 1$ - The total time is distributed among all disciplines.
b) **Minimum requirements:** $H_i \geq Hmin_i$ for all i=1...m - each discipline has a minimum required volume.
c) **Maximum constraints:** $H_i \leq Hmax_i$ for all i=1...m - preventing excessive time concentration.
d) **Curriculum requirements:** $\sum_{i \in S_k} H_i \geq Hreg_k$ for all k=1...p - compliance with regulatory requirements for discipline course modules, where S_k is the set of disciplines in the k-th course module.
e) **Logical dependencies:** $H_{prereq} \leq H_{main}$ - sequence of discipline study.

Optimization Algorithm

The optimization problem is solved using an iterative method:

$$H_i^{t+1} = H_i^t + \alpha * \frac{\partial F}{\partial H_i}, \qquad (4)$$

where t is the iteration number, α is the learning rate, and $\partial F/\partial H_i$ is the gradient of the objective function concerning the time proportion of discipline i. The gradient of the objective function is calculated as:

$$\frac{\partial F}{\partial H_i} = \sum \left(W_j * K_{ij} * T_i\right) \qquad (5)$$

The process continues until convergence is achieved or the stopping criterion is met:

$$\left|F^{t+1} - F^t\right| < \varepsilon, \qquad (6)$$

where ε is the specified precision.

IV. Experimental Validation of the Competency-Based Model for Master's Curriculum Optimization

The experimental mathematical model was validated using the 2018 master’s curriculum in “Software Engineering” at the National Polytechnic University of Armenia. All components of the methodology were systematically applied to optimize the program’s structure.

The baseline curriculum comprises 120 credit units across four semesters with the following distribution: general cultural disciplines 12.5% (15 credits), general professional disciplines 20.0% (24 credits), professional disciplines 52.5% (63 credits), and research component 15.0% (18 credits). This distribution demonstrates a traditional structure with predominance of professional disciplines and insufficient research representation, which does not correspond to contemporary requirements for research-oriented master's education.

Implementation of Adapted Stakeholder Requirements Analysis

The empirical foundation of the study consisted of a purposefully formed sample of n=105 research participants, including representatives from four key stakeholder groups. The sample structure ensured proportional representation of IT industry employers (33.3%), master's program graduates from 2019-2023 (38.1%), faculty implementing master's programs (19.0%), and representatives of professional communities (9.5%).

The fundamental distinction of the employed instrumentation was the adaptation of the questionnaire to the specificity of master's level education. Research participants evaluated competencies across six groups: Research, Digital Technologies, Systems Thinking, Entrepreneurial, Communication, and Language competencies, using a 10-point scale that considered their master's research orientation.

Determination of Competency Weight Coefficients

Based on average ratings across all participant groups, final mean values were calculated for each competency, which competency groups then aggregated.

Application of the normalization formula (1) to the results of the adapted stakeholder survey yielded the following distribution of competency weight coefficients for master's level education (Table 1):

Table 1. Distribution of Weight Coefficients

Competency Group	Weight Coefficient (W_j)	Proportion (%)
Research	**0.258**	**25.8%**
Digital Technologies	**0.238**	**23.8%**
Systems Thinking	0.213	21.3%
Entrepreneurial	0.177	17.7%
Communication	0.152	15.2%
Language	0.118	11.8%

The weight coefficient distribution demonstrates priority of research competencies (25.8%) and digital technologies (23.8%) for master's education. This differs significantly from the baseline 2018 curriculum, with only 15.0% research allocation and fragmentary digital technology representation, revealing substantial optimization potential requiring a 10.8 percentage point increase in research competencies.

Construction of Discipline-Competency Correspondence Matrix

Fifteen faculty experts assessed discipline-competency connection coefficients K_{ij} using a 0-1 scale, providing a quantitative characterization of each discipline's influence on competency formation. Analysis revealed an uneven distribution of competency formation potential among baseline curriculum disciplines.

Table 2. Correspondence Matrix for Key Disciplines of the Baseline Curriculum

Discipline	Research	Digital Technologies	Systems Thinking	Entrepreneurial	Communication	Language
Information Technologies	0.3	**0.9**	0.4	0.2	0.1	0.1
Research Work	**0.95**	0.3	0.7	0.1	0.4	0.2
Algorithms and Data Structures	0.4	**0.8**	**0.9**	0.1	0.2	0.1
Web Technologies	0.2	**0.85**	0.6	0.3	0.2	0.1
Research Seminar	**0.8**	0.2	0.5	0.2	**0.9**	0.3
Foreign Language	0.1	0.1	0.1	0.1	0.4	**0.95**
Software Engineering Methodology	0.6	0.4	**0.85**	0.2	0.3	0.1

Research work demonstrates maximum connection with research competencies (K=0.95), information technologies with digital competencies (K=0.9), and software engineering methodology with systems thinking (K=0.85).

Discipline type coefficients T_i were differentiated based on methodological characteristics: lecture courses - 1.0 (baseline level), practical sessions - 1.2 (enhanced skill formation), research activities - 1.5 (maximum impact on competencies), seminars - 1.3 (communication skills development).

Calculation of Competency Formation Levels

Application of formula (2) to the baseline curriculum structure required preliminary determination of instructional time proportions H_i for key disciplines (Table 3):

Table 3. Instructional Time Proportions of Baseline Curriculum Disciplines

Discipline	Credits		H_i	T_i
Information Technologies	**9**		**0.075**	**1.2**
Research Work	**5**		**0.042**	**1.5**
Research Seminar	**16**		**0.133**	**1.3**
Software Engineering Methodology	**5**		**0.042**	**1.0**
Algorithms and Data Structures	**5**		**0.042**	**1.2**
Web Technologies	**4**		**0.033**	**1.2**
Academic Foreign Language	**4**		**0.033**	**1.0**
Other Disciplines	**72**		**0.600**	**1.0**
Total	**120**		**1.000**	**-**

Based on these H_i values and expert-determined coefficients K_{ij}, quantitative assessments of formation levels for each competency group were obtained: research competencies are formed at level 0.373, digital technologies - 0.511, systems thinking - 0.494, entrepreneurial competencies - 0.179, communication - 0.348, language - 0.118.

Integral Assessment of Educational Program Quality

Calculation of the objective function (3) for the baseline curriculum yielded $F_{baseline}$=0.422. This indicator characterizes the degree of correspondence between educational program structure and stakeholder requirements and serves as the foundation for subsequent optimization.

Application of Curriculum Structure Optimization Algorithm

Calculation of partial derivatives of the objective function (5) revealed priority directions for curriculum structure optimization. The maximum gradient value is observed for research work (0.368), indicating the need for a substantial increase in its proportion within the curriculum. High gradient values are also characteristic of modern digital technologies (0.257) and systems analysis (0.181).

Application of the iterative algorithm (formula (4)) with learning rate $\alpha = 0.05$ and stopping criterion $\varepsilon = 0.001$ required 55 iterations to achieve convergence. The optimization process was characterized by monotonic growth of the objective function from an initial value of 0.422 to a final 0.782, corresponding to an 84.8% improvement.

Optimization dynamics demonstrated the most intensive growth of the objective function during initial iterations (the first 20 iterations provided an increase of 0.201), which is related to the adjustment of the most critical parameters of curriculum structure.

Optimization Results: Comparative Analysis of Structural Changes

The application of the developed mathematical model to the baseline 2018 curriculum resulted in a substantial transformation of the educational program structure. Comparative analysis of key parameters demonstrates significant improvements across all optimization directions:

Table 4. Comparative Analysis of Curriculum Structural Parameters

Indicator	**Baseline 2018 Plan**	**Optimized Plan**	**Change (%)**
Discipline Course Modules:			
Research disciplines	18 credits (15.0%)	28 credits (23.3%)	**+55.6%**
Digital technologies	9 credits (7.5%)	16 credits (13.3%)	**+77.8%**
General cultural disciplines	15 credits (12.5%)	11 credits (9.2%)	-26.7%
General professional	24 credits (20.0%)	20 credits (16.7%)	-16.7%
Workload Parameters:			
Classroom workload	920 hours (25.6%)	768 hours (21.3%)	**-16.5%**
Independent work	2680 hours (74.4%)	2832 hours (78.7%)	**+5.7%**
Workload variation coefficient	CV = 0.166	CV = 0.027	**-83.7%**
Quality Indicators:			
Objective function value	F = 0.422	F = 0.782	**+85.3%**
Research competency level	$C_1 = 0.373$	$C_1 = 0.584$	**+56.6%**
Digital competency level	$C_2 = 0.511$	$C_2 = 0.695$	**+36.0%**

Mathematical optimization transformed the baseline curriculum across four directions: strengthened research orientation (+55.6%), modernized technological component (+77.8%), optimized classroom/independent work balance (-16.5%/+5.7%), and improved integral program quality (+85.3%).

The obtained results demonstrate the effectiveness of the proposed competency-based model and confirm the possibility of significant quality improvement in master's programs through mathematically substantiated optimization of their structure.

V. Conclusion

This study developed and validated a competency-based model for master's curriculum development, addressing the mismatch between existing programs and contemporary master's education needs.

The model integrates adapted stakeholder requirements analysis with mathematical multi-criteria optimization, ensuring objective substantiation of curriculum structural decisions through quantitative assessment methods.

Experimental validation demonstrated high effectiveness: 85.3% increase in integral quality indicators, optimized research-oriented structure, and strengthened technological competencies. Results showed 87.3% correspondence with current educational standards, confirming model adequacy.

Scientific novelty includes specialized methodology for master's education, mathematical formalization of educational planning, and optimization algorithms accounting for multiple constraints. Practical significance enables evidence-based master's program design and development of methodological recommendations for educational institutions.

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